NASA's Certification and Qualification Strategies for Additive Manufactured Parts for Manned Spaceflight and their Application to TPS Materials

Rick Russell[1], NASA Technical Fellow for Materials
Copper Snapp[2], Spacecraft Systems Lead – TPS/MMOD/PROPULSION
Commercial Crew Program

[1]NASA Langley Research Center, [2]NASA Johnson Space Center

Additively Manufactured Thermal Protection System (AMTPS) Phase 2 Workshop
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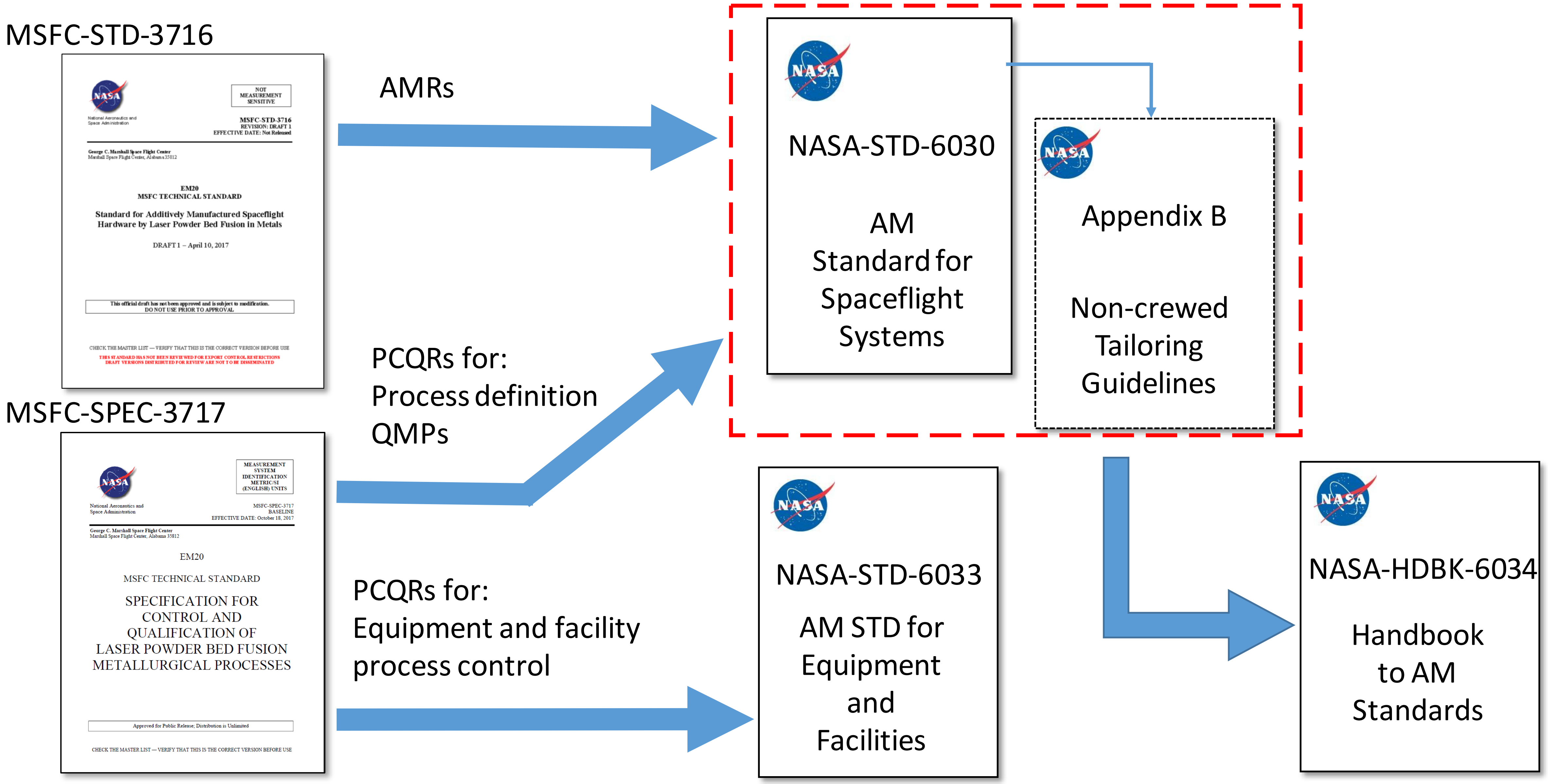
Additive Manufacturing (AM) at NASA

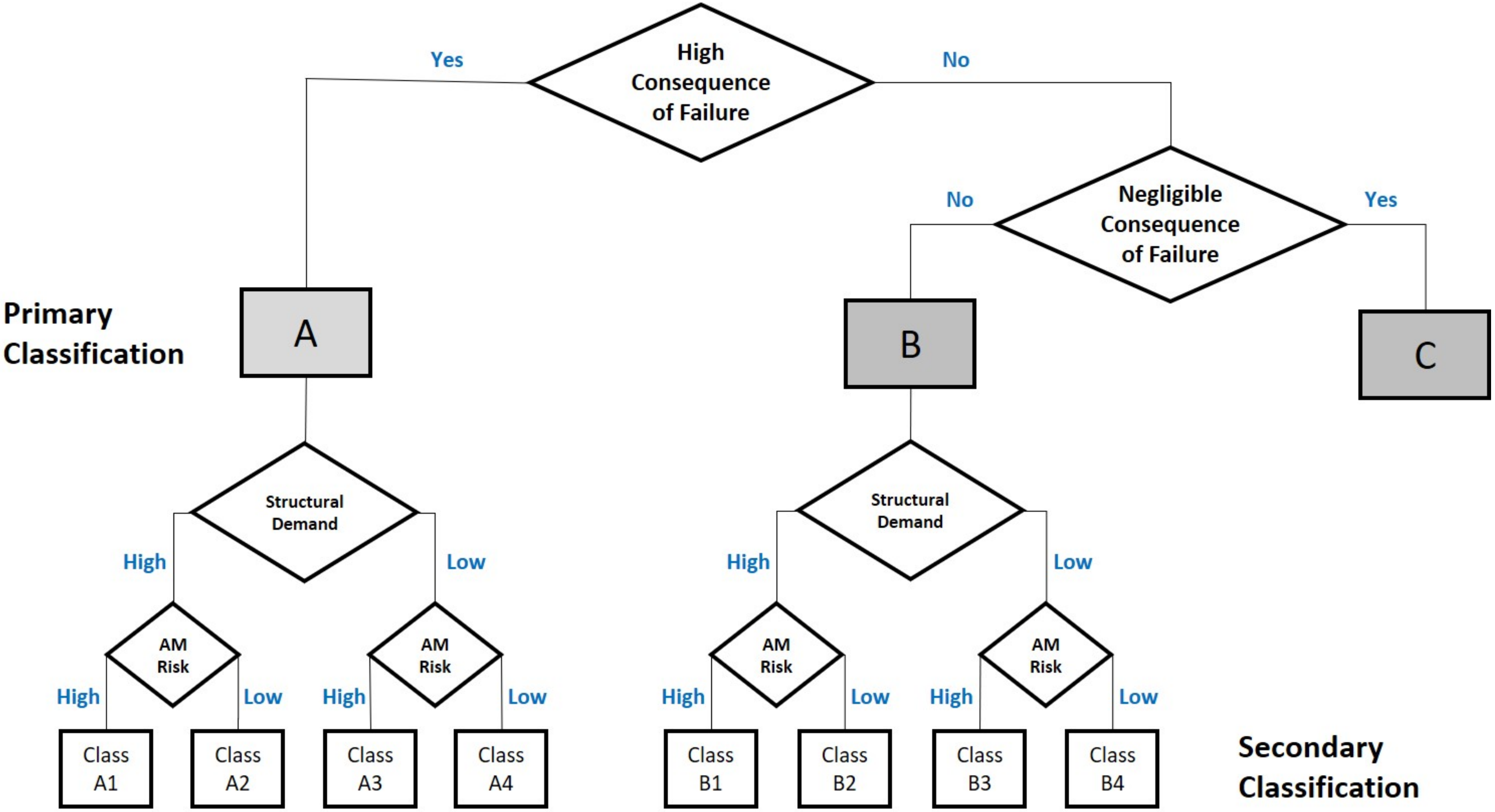
- Fully embraces advantages of AM
  - Cost/lead time/part count reduction, new design and performance opportunities, rapid design-fail-fix cycles
- While fully understanding the challenges
  - Especially in delivering high value, high performance AM hardware
- NASA has dual roles
  - Drive and foster AM technology research and development in support of broad industry adoption and industrialization
  - Develop protocols for spaceflight hardware certification for access to space that can safely meet mission objectives

Today's focus
Compare and contrast
With TPS cert strategies

New Agency Document Structure



Classification



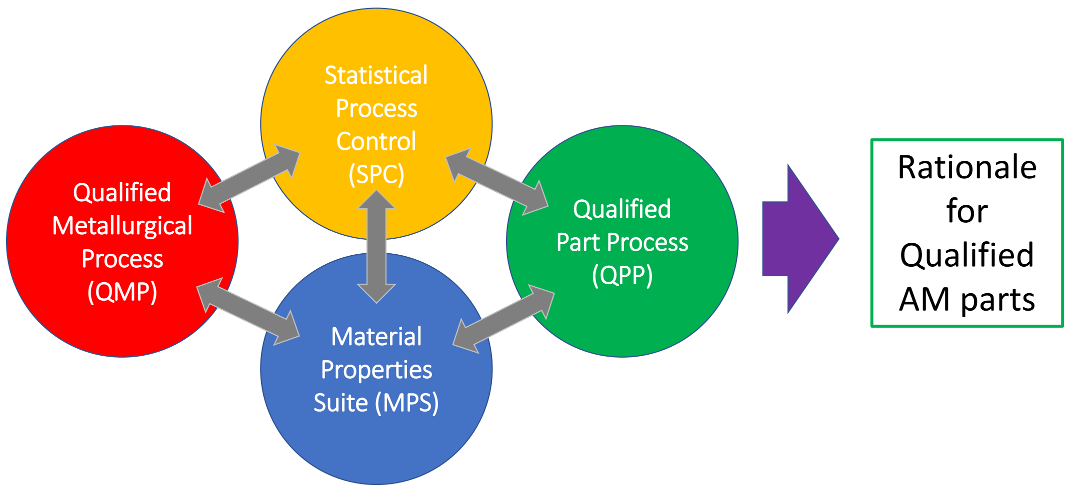
Applicability

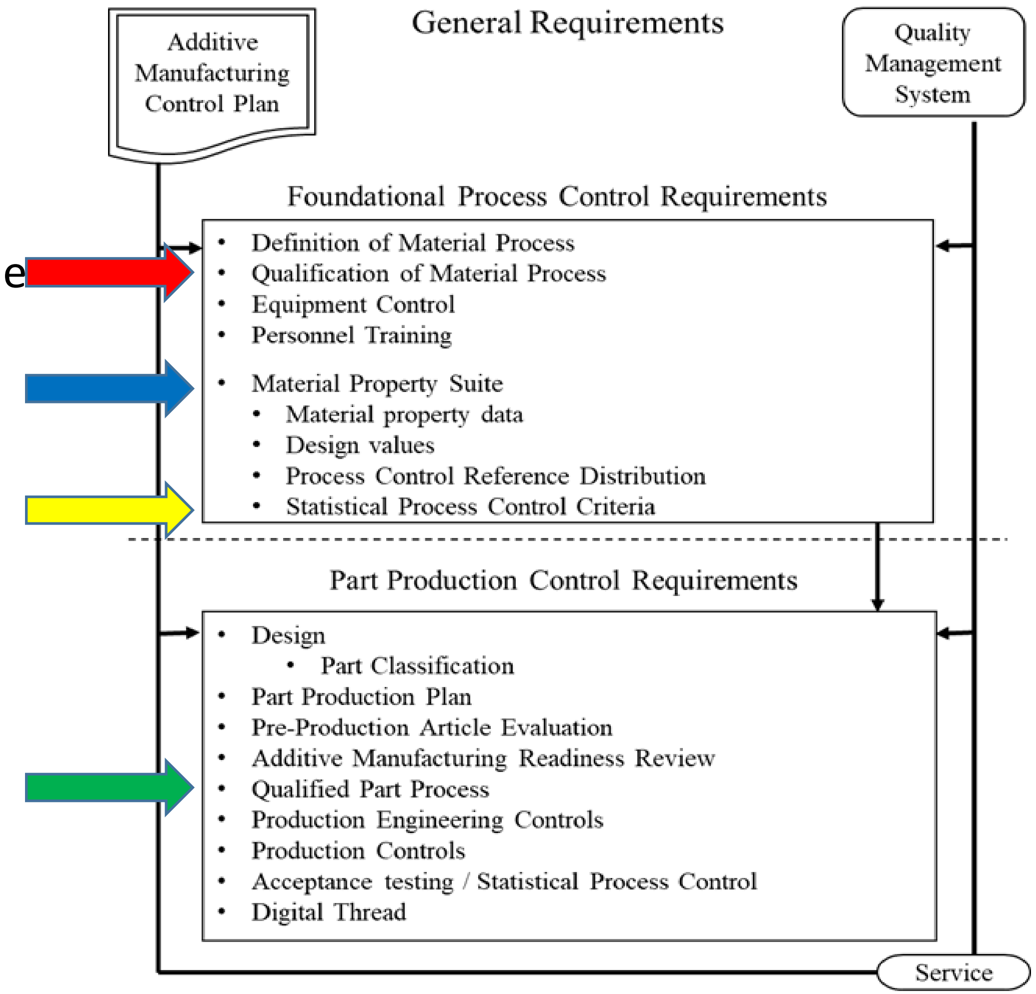
Category	Technology	Materials Form	Class A	Class B	Class C
Metals	L-PBF	Metal Powder	X	X	X
	DED	Metal Wire	X	X	X
	DED	Metal Blown Powder	X	X	X
Polymers	L-PBF	Thermoplastic Powder		X	X
	Vat Photopolymerization	Photopolymeric Thermoset Resin			X
	Material Extrusion	Thermoplastic filament			X

- Adaptive technologies, where the heat input can change during the manufacturing process, are not allowed
  - e.g. Electron beam powder bed fusion (E-PBF)

Summary of Methodology

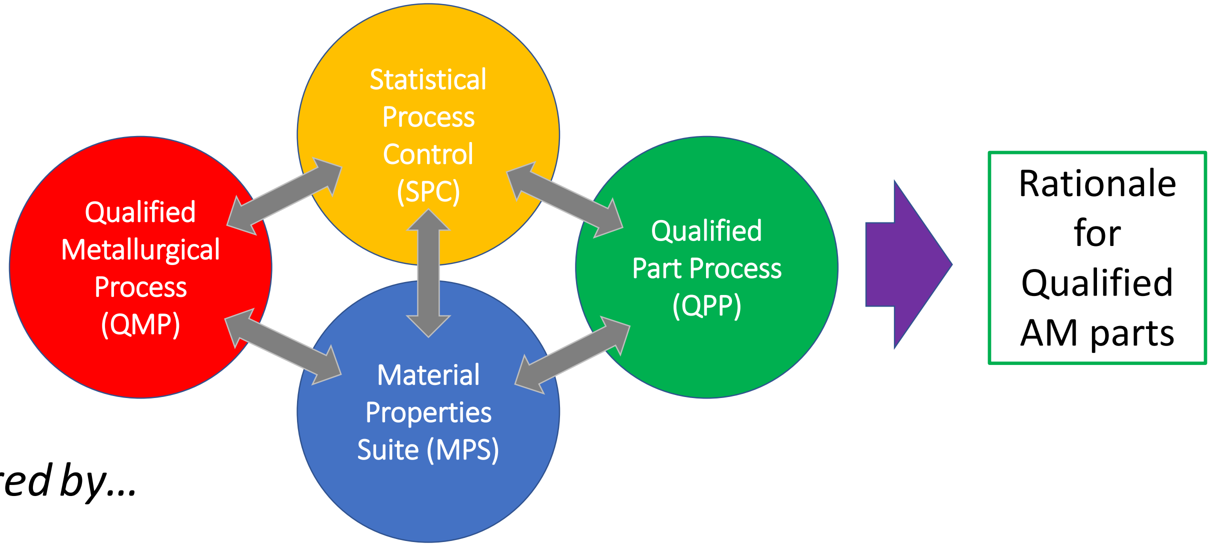
- General Requirements
  - Additive Manufacturing Control Plan (AMCP) and Quality Management System (QMS)
  - Backbone that defines and guides the engineering and production practices
- Foundational Process Control Requirements
  - Includes the requirements for AM processes that provide the basis for reliable part design and production
- Part Production Control Requirements
  - Includes design, assessment controls, plans (PPP), preproduction articles and AM production controls





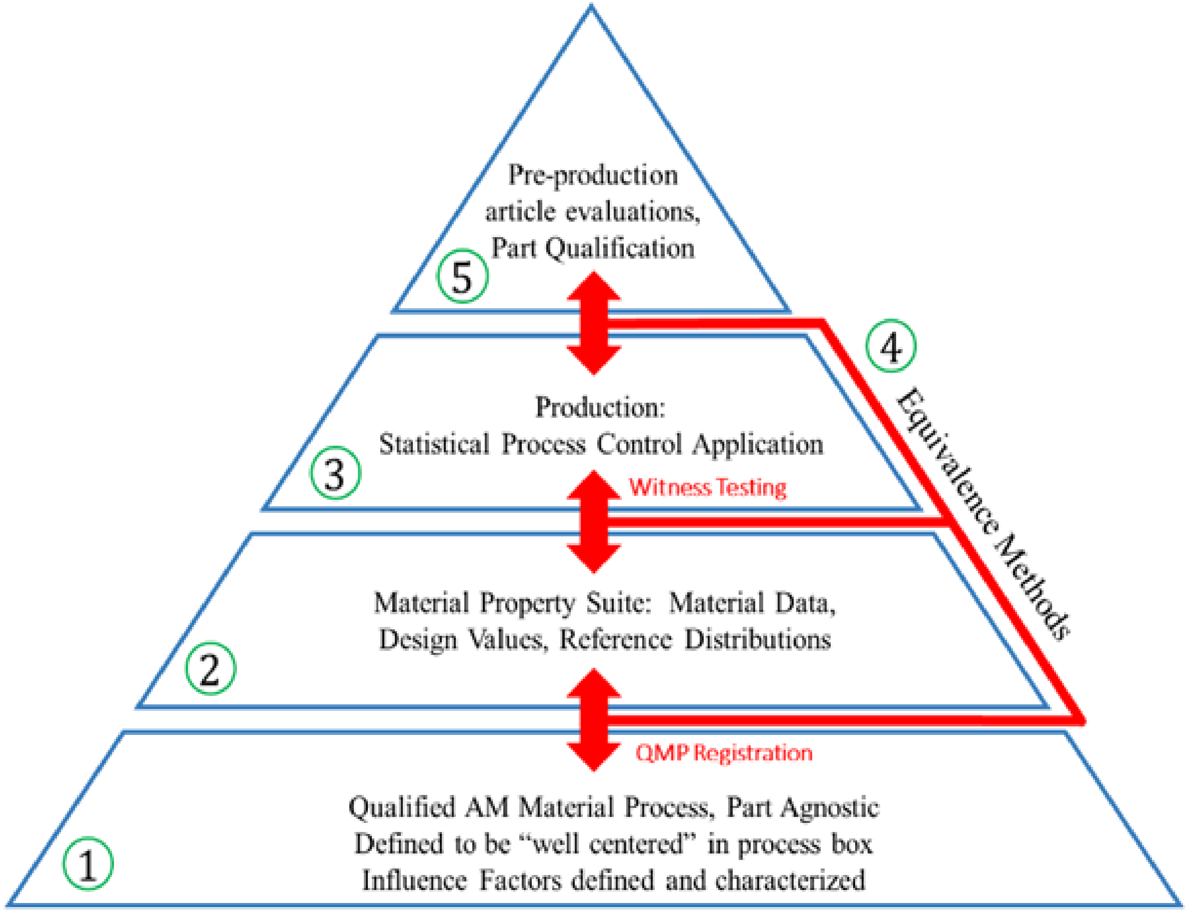
QMP: Qualified Material Process

- Begins as a <u>Candidate</u> QMP
- Defines aspects of the basic, <u>*part agnostic*</u>, fixed AM process:
  - Feedstock Controls
    - What you are building with
  - Fusion Process
    - How a machine operates
  - Thermal Process
    - Control what evolves your material state
- Qualification of the Candidate Material Process
  - Establishes a QMP: Qualified Material Process
  - Requirements vary based on classification
- Enabling Concept
  - Machine qualification and re-qualification, *monitored by…*
  - Process control metrics, SPC, *all feeding into…*
  - Design values



- AM machine and process are indelibly linked:
  - Step 1: Define a candidate process
  - Step 2: Qualify the candidate process to well-defined metrics

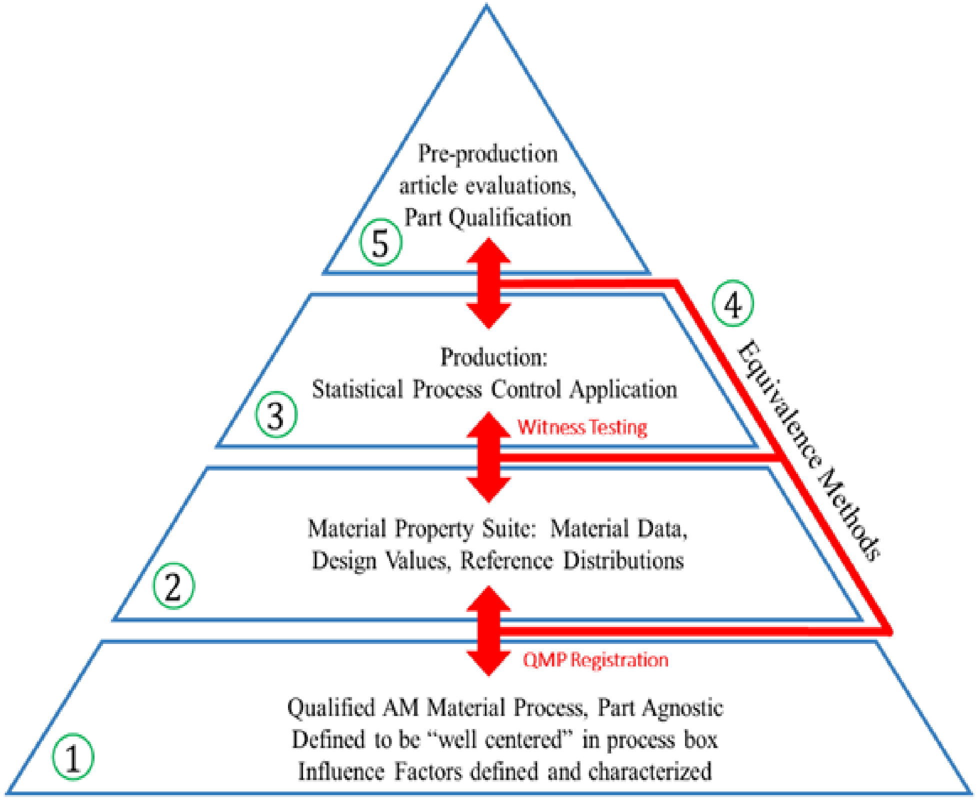
The QMP becomes the Foundation!



Material Properties

The <u>M</u>aterial <u>P</u>roperty <u>S</u>uite (MPS) consists of four inter-related entities:

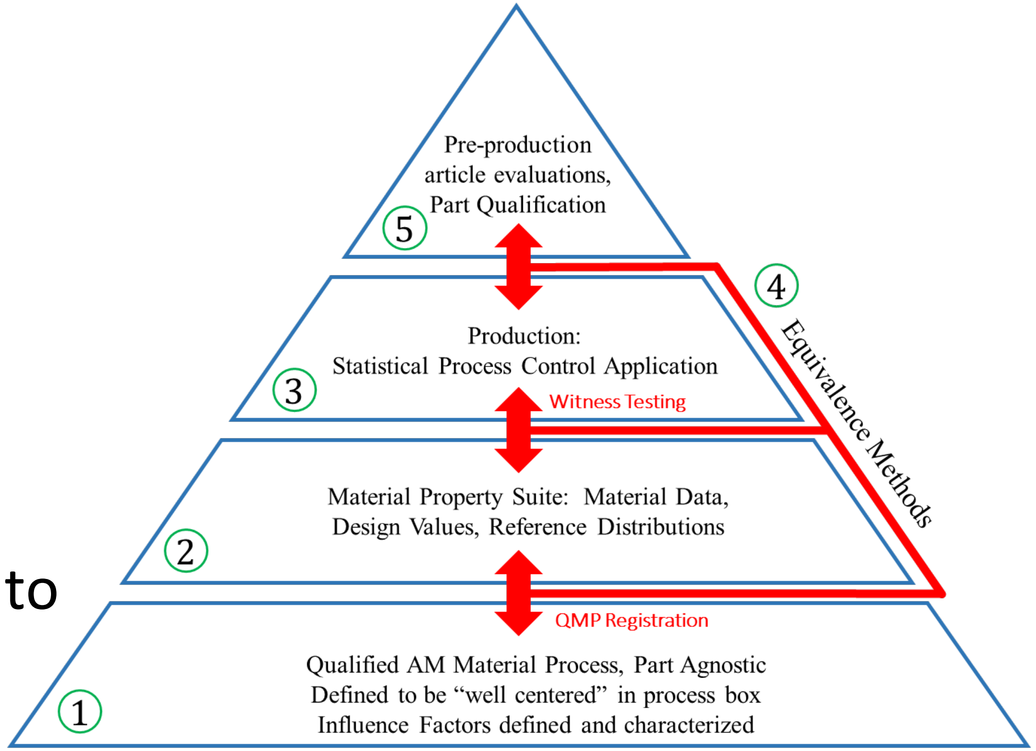
1. Data Repository
2. Design Values
3. Process Control Reference Distribution (PCRD)
4. SPC acceptance criteria for witness testing



Material Properties – SPC

Statistical process controls are important in sustaining certification rationale

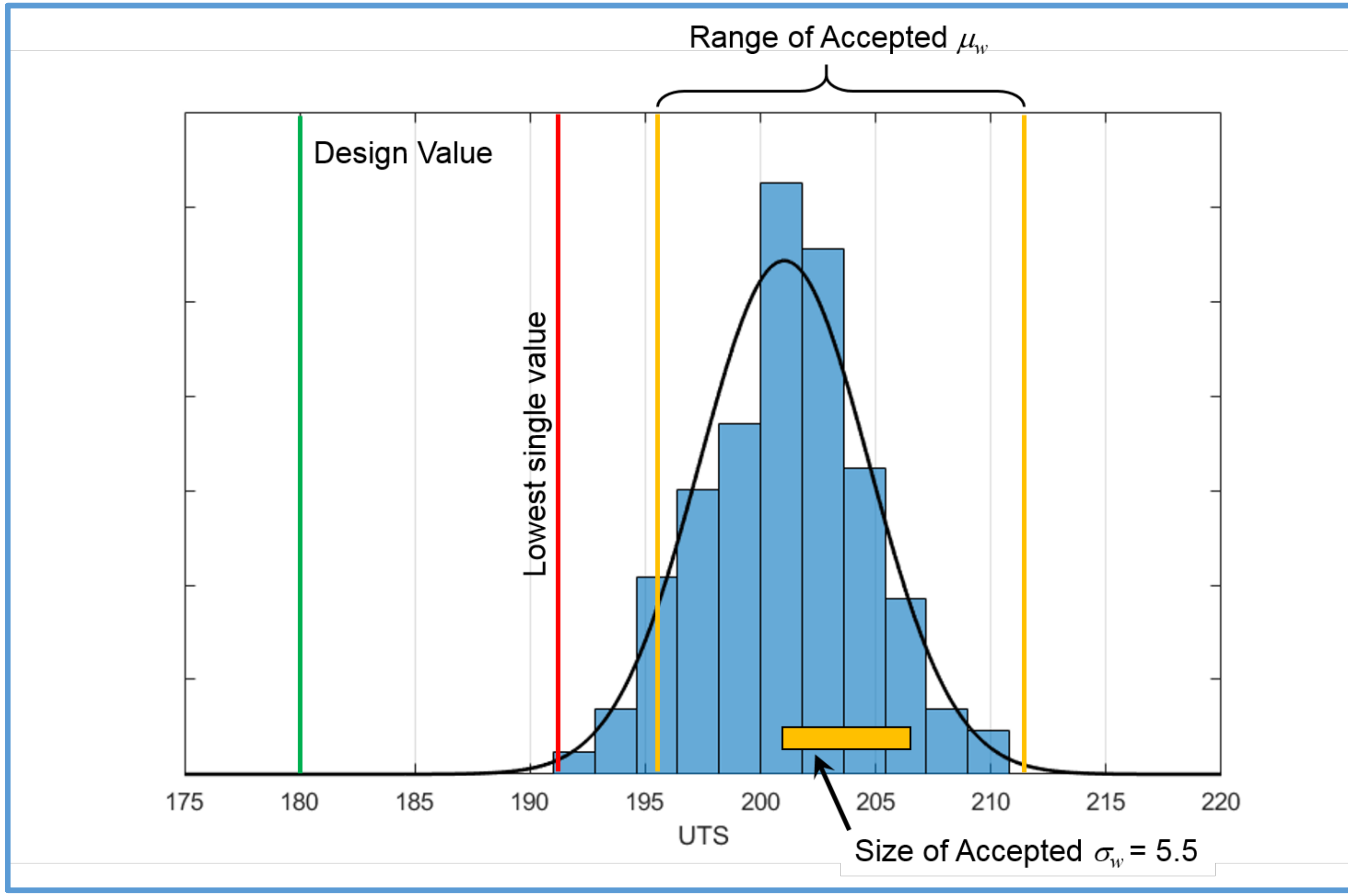
- *Statistical equivalency evaluations* substantiate design values and process stability build-to-build
  a) Process qualification
  b) Witness testing
  c) Integration to existing material data sets
  d) Pre-production article evaluations
- Equivalency of material performance is an anchor to the structural integrity rationale for additively manufactured parts



The dark and scary place most manufacturers are NOT used to operating….

Material Properties Suite – PCRD and SPC Criteria

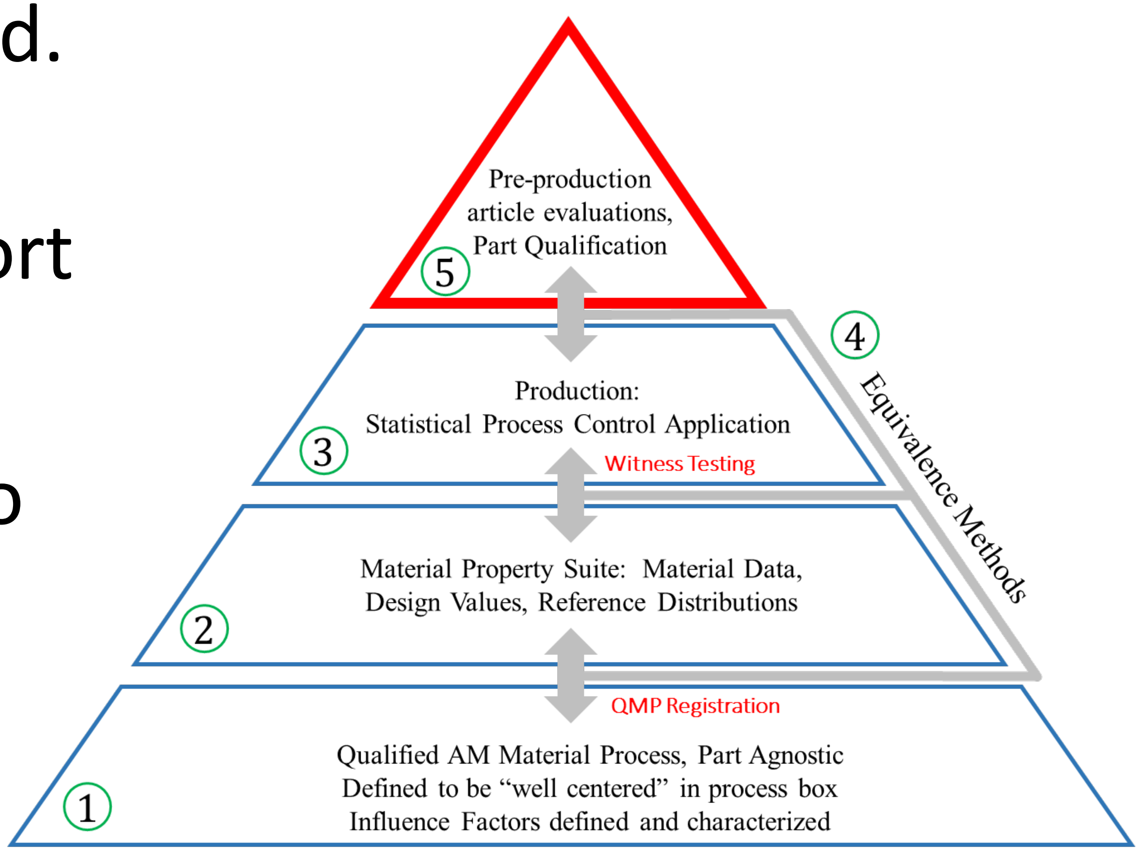
- Witness test acceptance is **not** intended to be based upon design values or "specification minimums"
- Acceptance is based on witness tests reflecting properties in the MPS used to develop design values
- Suggested approach
  - Acceptance range on mean value
  - Acceptance range on variability (e.g., standard deviation)
  - Limit on lowest single value



Foundation Complete!!

A basis to begin designing AM parts with certification intent is feasible once the foundation is laid.

Foundation is now ready to support AM part development in an environment with suitable rigor to establish certification.



AM Part Production

1. Follow the plan, always, with no short-cuts
2. Do not change a Qualified Part Process without re-qualification
3. Efficiency in process monitoring is critical to minimize the inevitable disruption
    - Witness tests can take considerable time to complete
    - Track the performance of each machine using all available metrics by control chart
    - In-process monitoring may provide early warning of changes in machine performance
4. Emphasize the importance of inspection for every part
    - Not just NDE, but visual inspection of as-built conditions
    - Watch for changes in part appearance – colors, support structure issues, witness lines/shifts
5. Consider systemic implications for all non-conformances

Summary

1. Certification rationale is most heavily rooted in the foundational controls
2. Part Planning must confirm the foundation produces a good part consistently
3. Part production follows a fixed process with statistical process controls

TPS Certification High Level Overview

- JSC-65827 – JSC TPS Design Standard
- NASA-STD-5021 – NASA TPS Design Standard

- The thermal protection system is designed to protect the vehicle from ascent and entry heating for nominal and the abort environment and is typically the first line defense against other environments.

- TPS's have been historically certified by analysis with data formulated in ground testing (arc jet, radiant) and then the test environment extrapolated to the flight environment.

- TPS is certified to withstand the stress environment that it is expected to see throughout the flight (flight loads, shock, thermal barrier loading, etc) and maintain positive margins.

- TPS is typically designed with no level of failure tolerance and considered a Criticality 1 system.
  - Also, could be Design for Minimum Risk (DFMR)
  - Crit 1 = Class A per NASA-STD-6030

- TPS relies heavily on the processing and testing such as bond verification to verify that the system can survive the expected flight environments

- TPS is typically very susceptible to impacts including those from the ascent environment and also MMOD.

History of TPS Certification

- Mercury / Apollo – Very heavy amounts of arc jet testing, 10,000's of tests throughout facilities around the country. Certified ablative material for flight, development of thermal ablation models for certification

- Shuttle – 1000's of tests performed in both the arc jet and radiant heat test facility. Reusable TPS that didn't require thermal ablation models. Simple 1D models typically used to verify tile thickness was sufficient.

- Orion – 1000's of arc jet tests performed for ablative TPS on the heat shield, 100's of radiant heat tests performed for the reusable TPS used on backshell

- Commercial Crew – 100's of tests performed, heavy reliance on what was previous done in TPS for past NASA programs. Thermal ablation models developed from sometimes less than 20 data points. SpaceX relies heavily on flight tests on un-crewed vehicles to understand how materials behave in flight environment rather than testing. (can we say this?)

TPS Environments (may not be all inclusive)

- The following environments are all areas that must be considered for TPS certification:

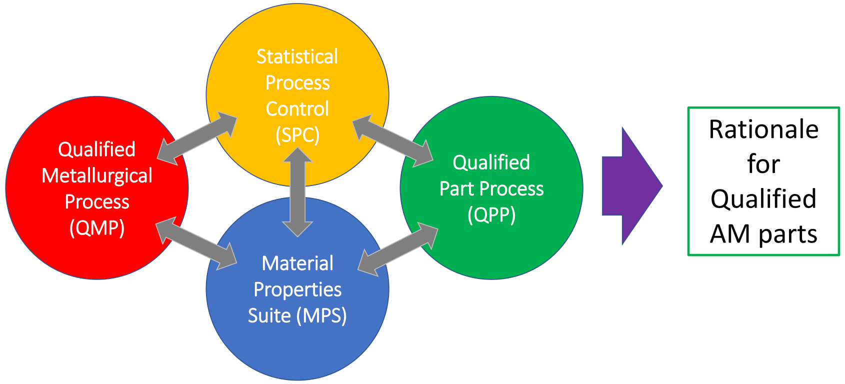
  - Impact Resistance
  - Damage Tolerance
  - Structural Deflections
  - Mechanical Loads
  - Acoustic Loads
  - Aerodynamic Loads
  - Vibration Loads
  - Shock Loads
  - Acceleration
  - Venting
  - Absorption
  - Rain/Hail
  - Lightning/Wind
  - Blowing Sand and Dust
  - Flora and Fuana
  - Fungi and Bacteria
  - Vacuum
  - Solar Radiation
  - Deep Space Radiation
  - Thermal Cycling
  - Atomic Oxygen
  - Ozone
  - MMOD

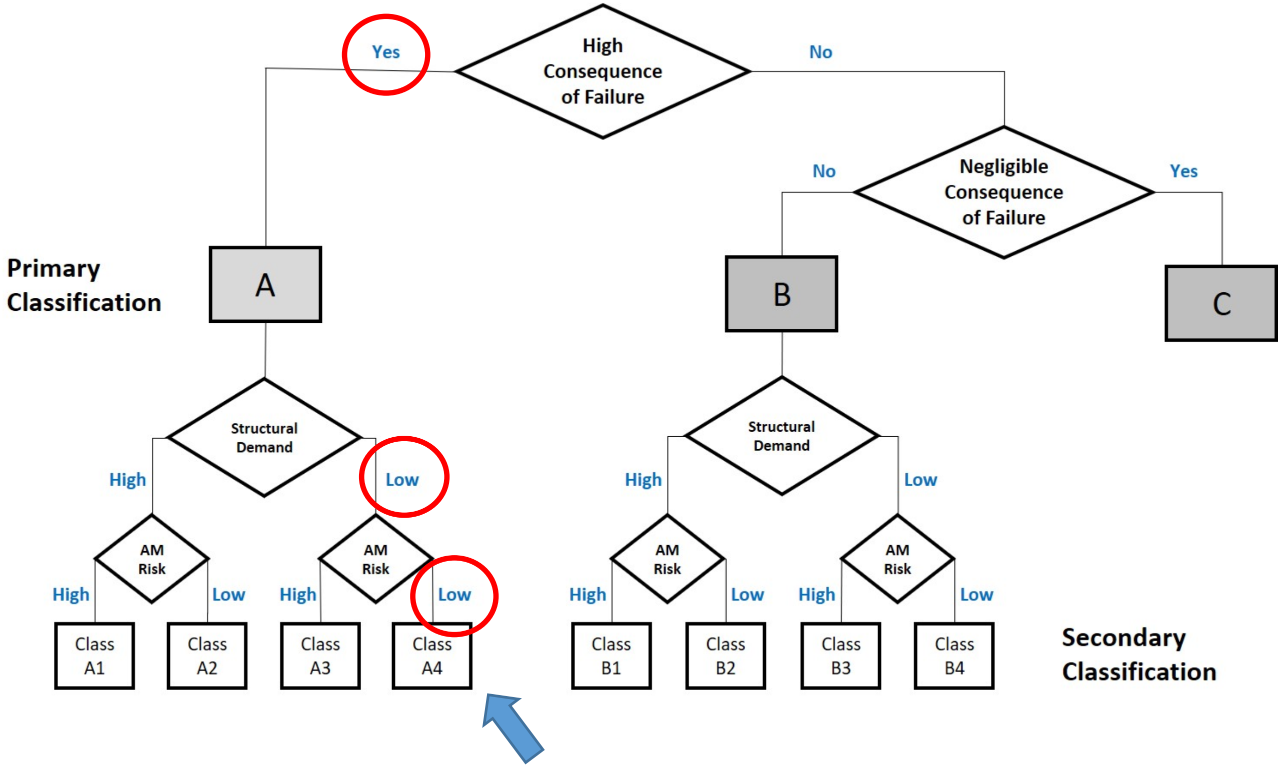
TPS Material Properties (may not be all inclusive)

- The following material properties are typically required to perform certification analysis:
  - Density
  - Thermal conductivity
  - Specific heat
  - Hemispherical emissivity
  - Solar absorptivity
  - Coefficient of Thermal Expansion
  - Elastic Modulus
  - Shear Modulus
  - Heat of Pyrolysis (Ablators)
  - Heat of Combustion (Ablators)
  - Char Yield (Ablators)
  - Thermal-gravimetric analysis (Ablators)
  - Pyrolysis gas composition and Enthalpy (Ablators)
  - Virgin and Char Elemental Composition (Ablators)
  - Ultimate Strengths/Allowables in All Pertinent directions (A-basis or B-basis)

How would NASA-STD-6030 Principles be applied to TPS??

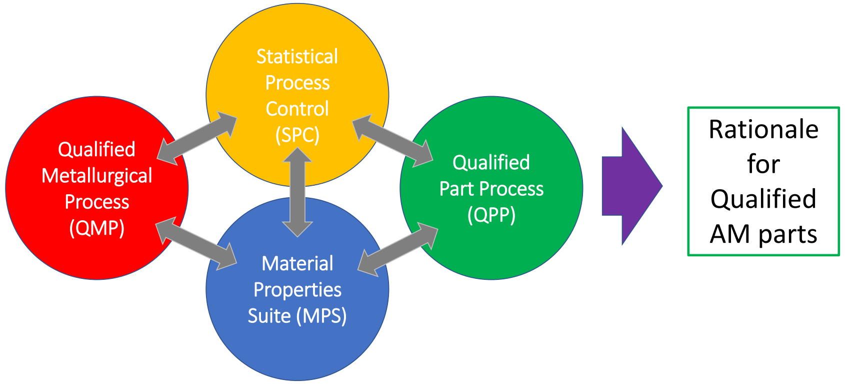
- Zero fault tolerant = Class A
  - Structural demand most likely low
  - AM Risk most likely low
  - Class A4





Consult 6030 for advice on types and number of process control samples

How would NASA-STD-6030 Principles be applied to TPS??



- Qualified Material Process
  - First step is to define a part agnostic fixed AM process
    - Feedstock (what you build)
    - Fusion (how you build)
    - Thermal processes (what controls end state)
  - Establish well-defined processing metrics and then qualify your process to them
  - Test, test, test until you are comfortable
    - Includes testing of “influence factors”*
  - Lock the process based on a dataset that fits your requirements

Influence factors are items that have the capability to alter the baseline performance
- Unique to AM process
- Environment

How would NASA-STD-6030 Principles be applied to TPS??

- Witness test acceptance is **not** intended to be based upon design values or “specification minimums”
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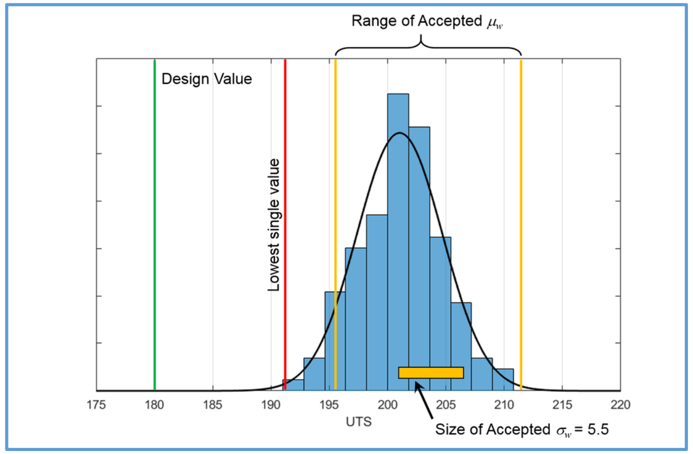
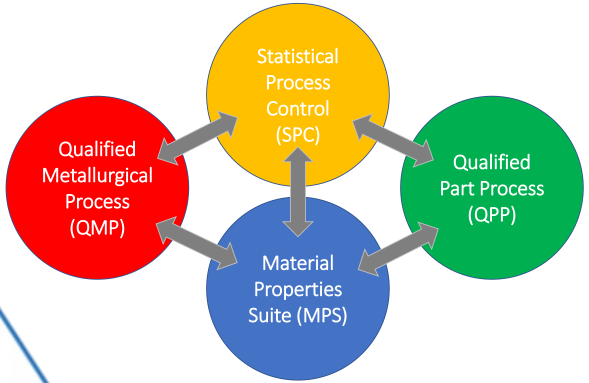
Q: So how are witness samples going to happen? Plugs? Witness plates??

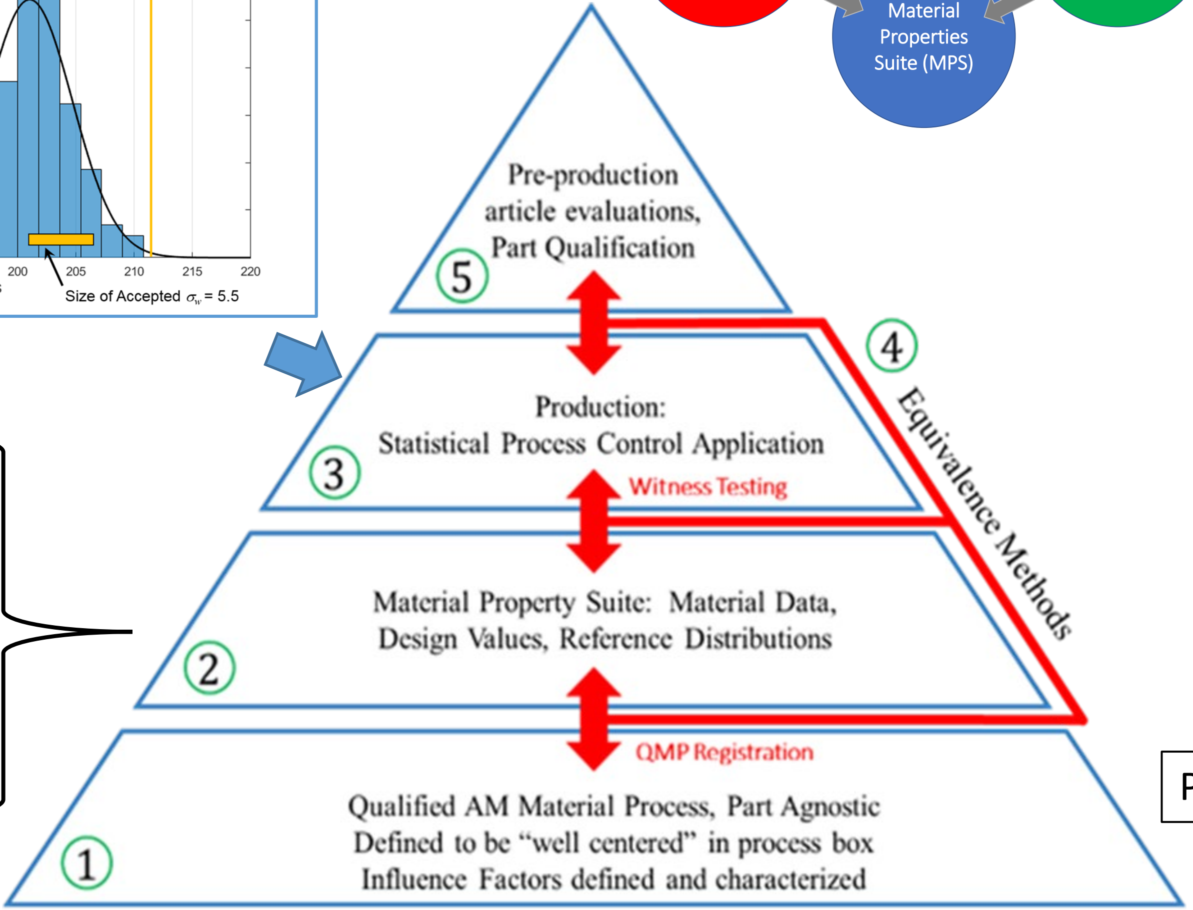




Rationale for Qualified AM parts

- Data Repository
- Design Values
- Process Control Reference Distribution (PCRD)
- SPC acceptance criteria for witness testing

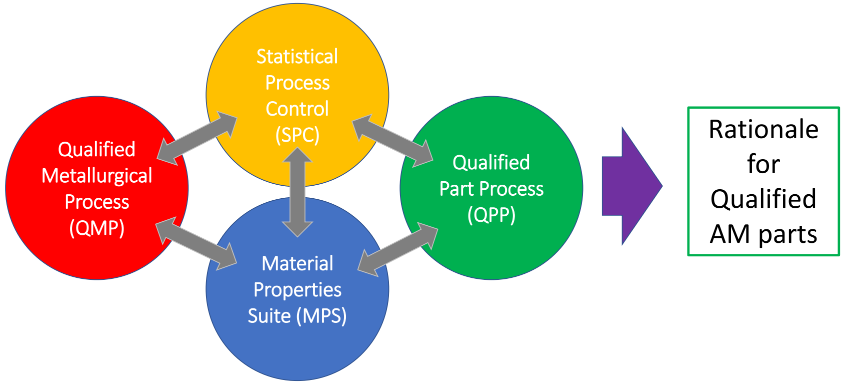
Part agnostic to part specific

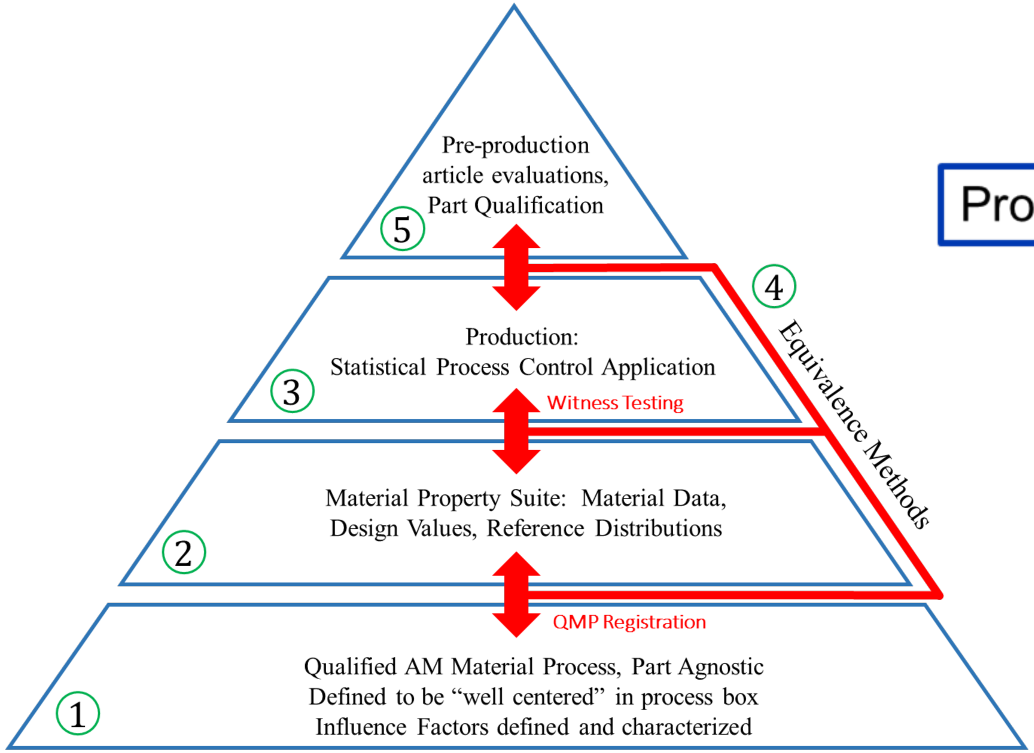


Part agnostic

How would NASA-STD-6030 Principles be applied to TPS??

- Equivalence methods

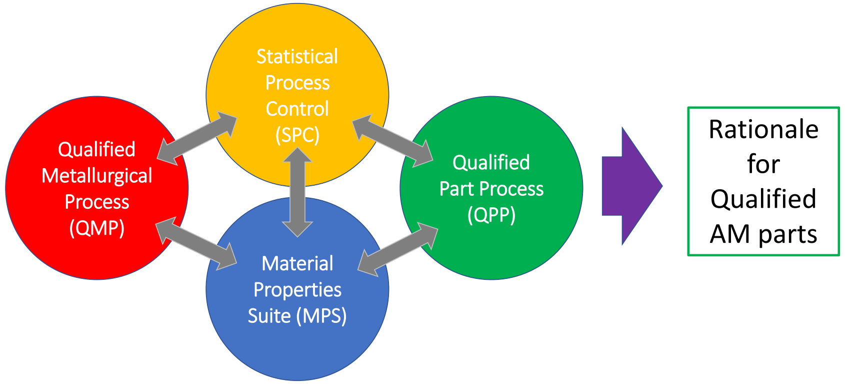




Process → Structure → Property → Performance

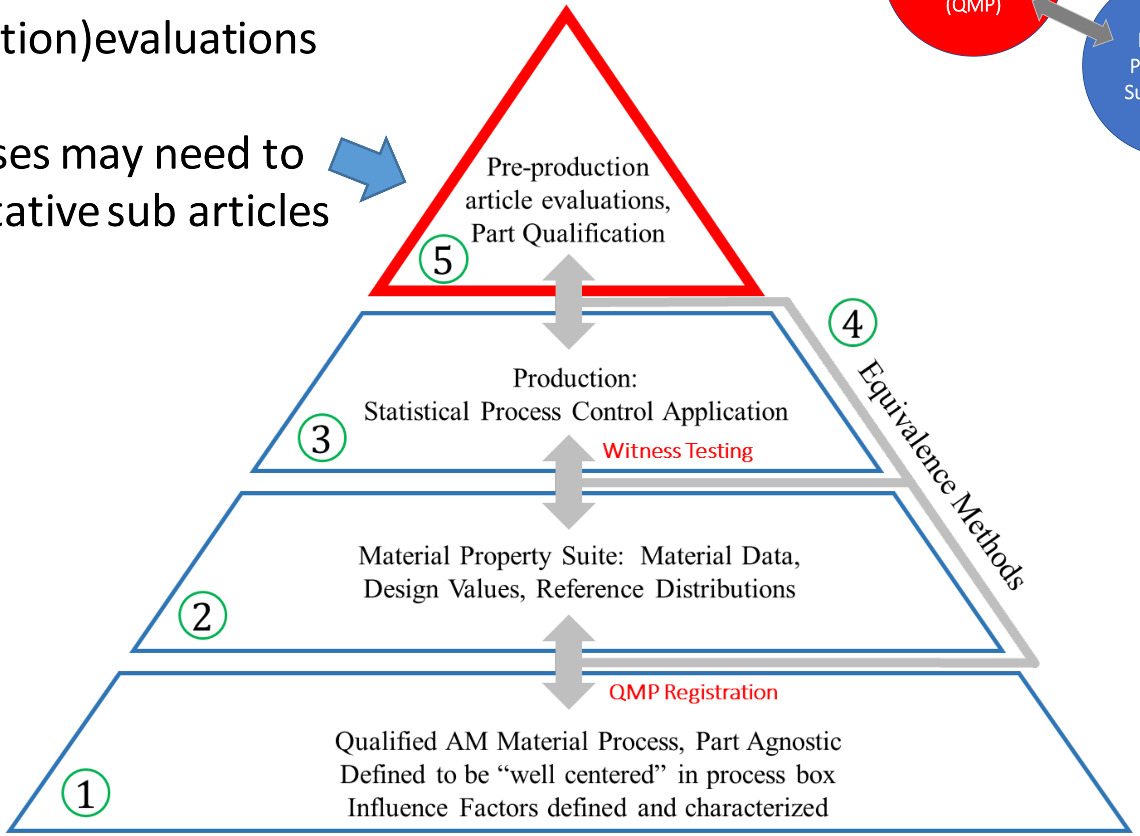
- Must evaluate the quality of AM TPS materials to assure that the broad range of characteristics meet all expectations.
- Need to map the process windows (e.g. environmental influence factors)

How would NASA-STD-6030 Principles be applied to TPS??



Normal first article (pre-production)evaluations and qualification protocol

- Easy for tiles but in other cases may need to reply on testing of representative sub articles or worst case geometries



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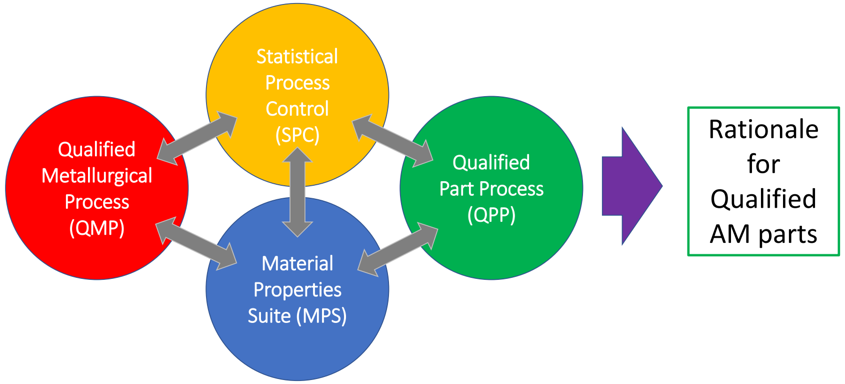

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